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Predicting the warm forming behavior of WE43 and AA5086 alloys

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Abstract

In the present work, we have studied the formability behaviour of two types of magnesium alloys, WE43 hot rolled and WE43 cold rolled by carrying out uniaxial tensile test at elevated temperatures of 350°C to 500°C both experimentally and numerically at a constant strain rate of $10^{-3}s^{-1}$. Finite element (FE) model is simulated in ABAQUS/CAE 6.7-6 using coupled temperature-displacement step at higher temperature considering material's property to be isotropic in nature. The effect of temperature on maximum flow stress and major strain at onset of necking is discussed. The true stress-strain behaviour and necking evolution through strain mapping are predicted from FE model and compared with the experimental results. The results show that with increase in temperature, the maximum flow stress decreases and necking delays with increase in limiting major strain for the Magnesium alloys. The work has been extended to predict the forming limit strains of Al 5086 alloy only on the negative minor strain region using M-K (Marciniak and Kuczynski) concept. An FE model based on M-K concept is simulated at 20°C, 150°C and 200°C using coupled temperature-displacement step considering anisotropic sheet material. A groove is created in the middle of the model with an optimized *f* value of 0.99, after much iteration.The forming limit strains from such FE simulations are compared with the available experimental data. The results are encouraging providing scope for further improvements in modelling.

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Keywords:Magnesium alloys; Warm sheet forming; Tensile test; Formability; Necking

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1. Introduction

With the advancement in science and technology, weight and number of the automobile is increasing which leads to increase in fossil fuel consumption and amount of carbon dioxide in air. Today the main focus of the automobile industries is to decrease vehicle's weight and make it environment friendly. In this area, lightweight materials such as aluminium and magnesium alloys are being used to manufacture automobile body parts [1]. In order to select accurate materials for engineering applications, tensile test is the most fundamental way of determining their properties. Magnesium alloys have poor formability at room temperature because of hexagonal close-packed (HCP) structure, therefore elevated temperature deformation of magnesium alloys are being studied. El-Magd and Abouridouane determined different failure criterion of AZ80 magnesium alloys by carrying out both experimentally and numerically quasi-static and dynamic tensile test at room temperature and elevated temperature [2]. Understanding the formability of magnesium alloys at various conditions is important. The effect of temperature, strain rate and material's anisotropic properties has a significant effect on its elongation at failure. Janik et al. carried out tensile test of as-cast AZ91 magnesium alloys at higher temperatures up to 375°C and varying strain rates for three cases of rolling direction (RD), transverse direction (TD) and 45° to RD, it was observed that at 350°C specimen elongated up to 200% until failure [3].

While manufacturing sheet metal, one of the problems associated with it is onset of localized necking which limits its formability. Formability limit curve (FLC) is useful to predict onset of necking in a sheet metal, and it can be obtained both experimentally and numerically, but experimental determination of FLC requires complex experimental setup which makes the process costly as well as time consuming. Ozturk and Lee performed experimental and numerical out-of-plane formability test on aluminium killed drawing quality (AKDQ) electrogalvanized steel. Effect of friction and mesh size was studied. Numerically it has been reported that the element size plays a significant role on strain localisation and advised to have mesh size bigger than sheet thickness [4]. Abedrabbo et al. performed numerical analysis of forming of aluminium alloys at elevated temperatures implementing coupled thermo-mechanical model to study stamping of sheet via punch. It was reported that for maximum formability of aluminium sheet lowest temperature of the punch is required [5]. Zhang et al.developed the method to predict the formability of sheet in-plane by creating a FE M-K model in ABAQUS code. User defined subroutine was implemented to incorporate constitutive law and different ratios of displacement were given as boundary conditions to obtain different strain paths in FLD [6].

In our present work, tensile test of dog bone shape of WE43 hot rolled and WE43 cold rolled magnesium alloys is carried out at elevated temperatures (T) from 350°C to 500°C at constant strain rate, $\dot{\varepsilon}$ of $0.001 s^{-1}$ both experimentally and numerically in ABAQUS/Standard using coupled temp-displacement as basic step in FE model. During simulation material properties are assumed to be isotropic in nature and tests are carried out considering isotropic hardening behaviour. Plots of true stress versus true strain, maximum flow stress versus temperature, saturation curve for the major strain in neck region versus shoulder region, and major strain in the shoulder region at the onset of necking versus temperature are predicted from FE model and compared with the experimental results.

To extend the formability analysis of lightweight alloys, FE model M-K concept of AA5086 is created in ABAQUS/CAE using coupled temp-displacement as basic step in FE model. Specimens are modelled at three different temperatures, 20°C, 150°C, and 200°C for geometrical non-homogeneity factor, f value of 0.99 of varying widths, w from 100mm to 200mm to obtain different strain paths. Specimens are pulled in one direction at constant velocity, v of 10mm/s for certain duration. FLC are predicted at three different temperatures and compared with the experimental FLC obtained by Chu et al. [7].

2. Methodology

The first subsection deals with the tensile test of WE43 Mg alloy and in second subsection numerical modeling for the prediction of formability of AA5086 Al alloy has been discussed in detail. The first subsection has been divided into two subsections, one for experimental details related to tensile testing of WE43 Mg alloy and second one focuses on the numerical modeling aspect of it.

2.1. Uniaxial tensile test of WE43 Mg alloys

2.1.1. Experiment

WE43 hot rolled and WE43 cold rolled sheets are fabricated using water jet cutting in RD to obtain dog bone samples of gauge length 12.5mm and gauge cross section of 6.4×2.6 mm and 6.2×1.6 mm respectively for uniaxial tensile test. Thickness of WE43 hot rolled is 2.6 mm and WE43 cold rolled is 1.6 mm.Samples are clamped on the holder of servo hydraulic 8872 Instron frame and uniaxial tensile tests are performed at elevated temperatures and constant strain rate of $0.001 s^{-1}$ until failure as mentioned in the Table 1. During the test, true stress versus true strain curve is constructed from the recorded extension and applied external load data.

Table 1Temperature and strain rate conditions during uniaxial tensile testing of WE43 hot rolled and WE43 cold rolled Mg alloys

Temperature (°C)	Strain rate (s^{-1})	Type of test
350	0.001	Un-interrupted
400	0.001	Un-interrupted
425	0.001	Un-interrupted
450	0.001	Un-interrupted
475	0.001	Un-interrupted
500	0.001	Un-interrupted

2.1.2. Numerical modeling

A 3D, deformable, and solid extrusion type FE-Model is created in ABAQUS/Standard using coupled temp-displacement as basic step. Dog bone shaped model of WE43 hot rolled and WE43 cold rolled are modelled taking into account the same dimensions which are used for experiments. Fig. 1 shows the geometrical dimensions of the FE-Model created during simulation.

In meshing part, C3D8RTwith element length of about 1.6 mm for WE43 cold rolled and 1.3 mm for WE43 hot rolled with linear geometric order are implemented as shown in Fig. 2. For WE43 cold rolled, there are 288 numbers of nodes and 117 numbers of elements and for WE43 hot rolled, there are 522 numbers of nodes and 288 numbers of elements. It has been observed from element sensitivity analyses that the effect of number of elements (1, 2 and 4 number of elements) along sample thickness is insignificant. There is not much different in the stress-strain behaviour and strain evolution during necking with number of elements along the sample thickness. The material property is taken as isotropic in nature. The true stress-strain data from experimental results at different temperatures are used as plastic properties during simulation of uniaxial tensile test. Both strain hardening and strain-rate sensitivity effects are neglected during the simulation. The value for Poisson's ratio is 0.27 and E is calculated from the experimental plot as per usual procedureand implemented in model. The specimen is given specified temperature as boundary condition. The lower part is fixed and the upper part is given velocity of 0.0125 mm/s in the pulling direction.

2.2. Numerical prediction of the formability limit of AA5086 Al alloy

A 3D, deformable, and solid extrusion type FE analytical M-K Model has been created in ABAQUS/Standard using coupled temp-displacement as basic step (Fig. 3). Anisotropic properties have been assumed during numerical analysis using Hill's 48 yield criterion [8]. Material constants for anisotropic properties are taken from the work of Chu et al. [7]. Tests are carried out for different values of width to get different strain paths for constant$f$value of 0.99 for three different temperatures of 20°C, 150°C and 200°C. The thickness of the groove (t_g) region is taken to be 1.98 mm and length of sample, L, 200 mm. The thickness heterogeneity has been made in CAD environment during FE simulations. A large number of C3D4T elements of 9431 for width of 100 mm to 22356 for width of 200 mm and number of nodes of 2998 for width of 100 mm to 7051 for width of 200 mm are meshed to avoid unnecessary stiffness of the element. Poisson's ratio of 0.3 and E is taken as 64 GPa. One end is fixed and other end is displaced with a constant velocity of 10 mm/s. Note, thickness of safer region is denoted by t_s.

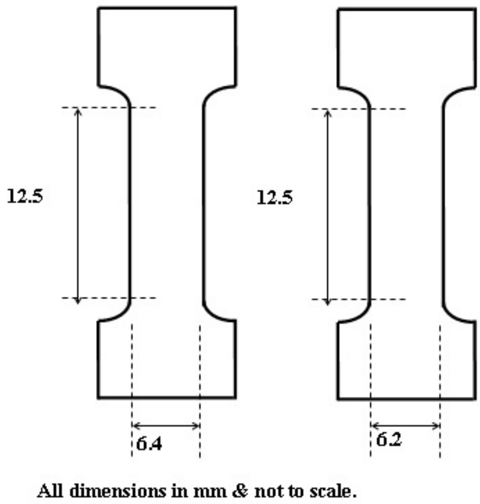

Fig. 1. WE43 hot rolled (left) and WE43 cold rolled (right)

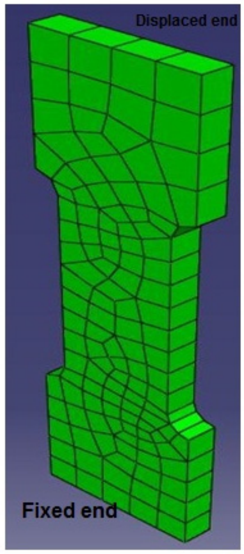

Fig. 2. Meshed tensile specimen

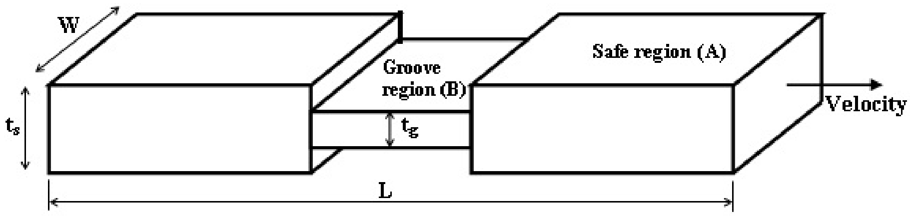

Fig. 3. FE model for M-K analysis

3. Results and discussions

Under this section, results of true stress versus true strain, true strain at onset of necking versus temperature, maximum flow stress versus temperature of WE43 Mg alloy and formability limit curve of AA5086 alloy have been presented and discussed in detail. The experiments and simulations have been done for six temperatures as mentioned above but in this section plots are presented only for few temperatures for pictorial clarity.

At higher temperature formability of magnesium alloys is increased due to the activation of additional slip planes and thus maximum flow stress (maximum true stress) decreases with increase in temperature as shown in Fig. 4. At higher temperature greater than 350°C, true stress versus true strain curve remains almost flat due to the dynamic balance between hardening and softening [9]. To plot the stress versus strain data from simulation, selection of mesh plays a significant role. Mesh with the maximum equivalent strain and near middle of the gauge portion of the dog bone specimen is selected to plot the above Fig. 4. At a temperature of 350°C, maximum flow stress of WE43 cold rolled is more than WE43 hot rolled due to its low gauge cross-section of 6.4 × 1.6 mm.

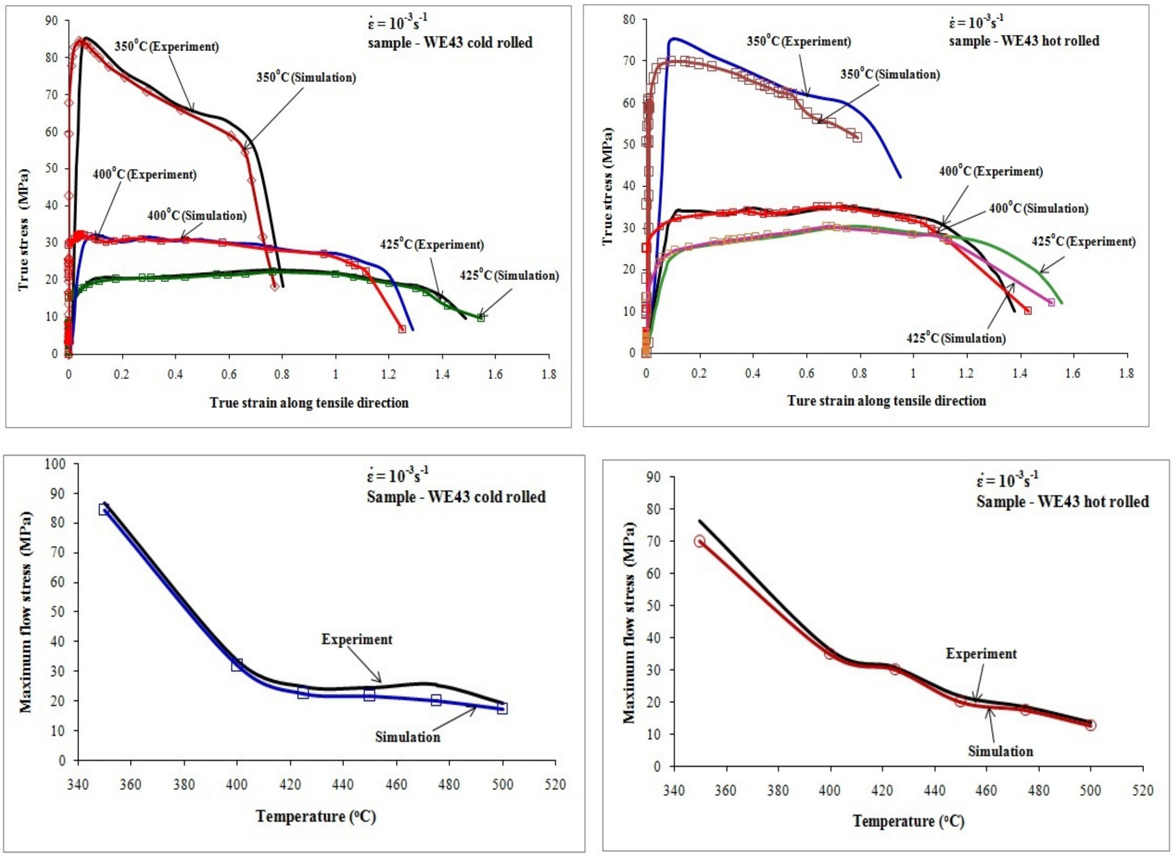

Fig. 4. Comparison between experiment and simulation result of stress-strain (above) and maximum flow stress-temperature (below)

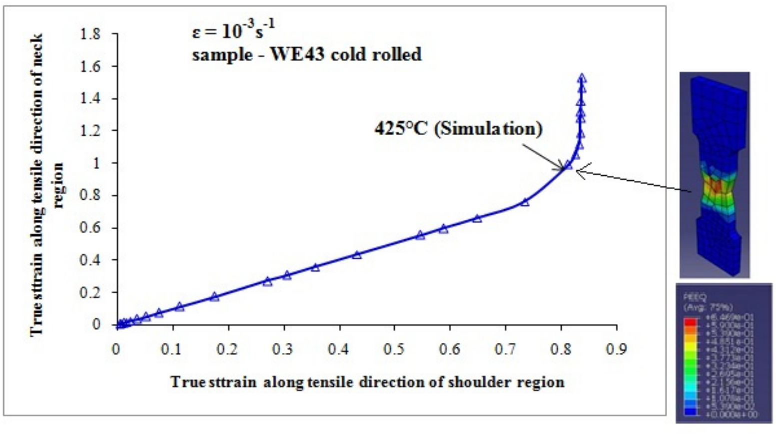

Fig. 5. True strain along tensile direction of neck region versus shoulder regionand the equivalent plastic strain distribution (at 425°C for WE43)

Due to the onset of necking, the strain in the neck portion is localised and it starts increasing at a faster pace as compared to the shoulder region and due to this one could expect a saturation nature between the plots of neck and shoulder region as shown in Fig. 5. From the contour plot of equivalent strain as shown in Fig. 5, the mesh with the maximum strain is selected as neck near the middle portion of the gauge. For shoulder region, mesh about 2 to 3 mm from the neck region is selected taking into consideration that simulation result is as close as possible to the experiment result. From Fig. 5, the moment saturation is observed, the true strain of the shoulder region is identified as onset of necking. Since stress is ratio of force to cross-sectional area of the gauge portion, therefore the moment stress reaches its maximum value, force also attains its maximum value and area of cross section in the gauge portion is minimum, i.e., necking has been initiated, therefore one can select the strain at onset of necking corresponding to the maximum true stress value from experiment results of true stress versus true strain plots as shown in Fig. 4.

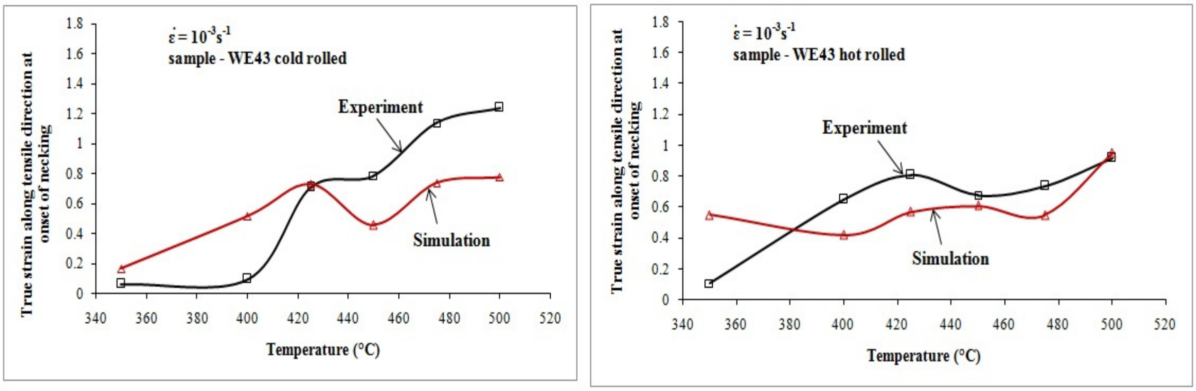

Fig. 6. Comparison between experiment and simulation results of true strain along the tensile direction at onset of necking versus temperature

Fig. 6 presents the comparison of experiment and simulation results of strain at onset of necking versus temperature for WE43 cold rolled and WE43 hot rolled. Simulation results are deviating significantly from the experiment result; this is because of the flattened portion of true stress versus true strain plot as shown in Fig. 4.For example,at 400°C, due to dynamic balance between hardening and softening, the identification of strain at the onset of necking might not be exact as it could occur between 0.1 to 0.8 true strain value as shown in Fig. 4. Another possible reason is selection of mesh for the shoulder region since selection of different mesh for shoulder region can shift the saturation curve left or right in Fig. 5 and thus value of strain at onset of necking will change thus leading to inaccuracy.

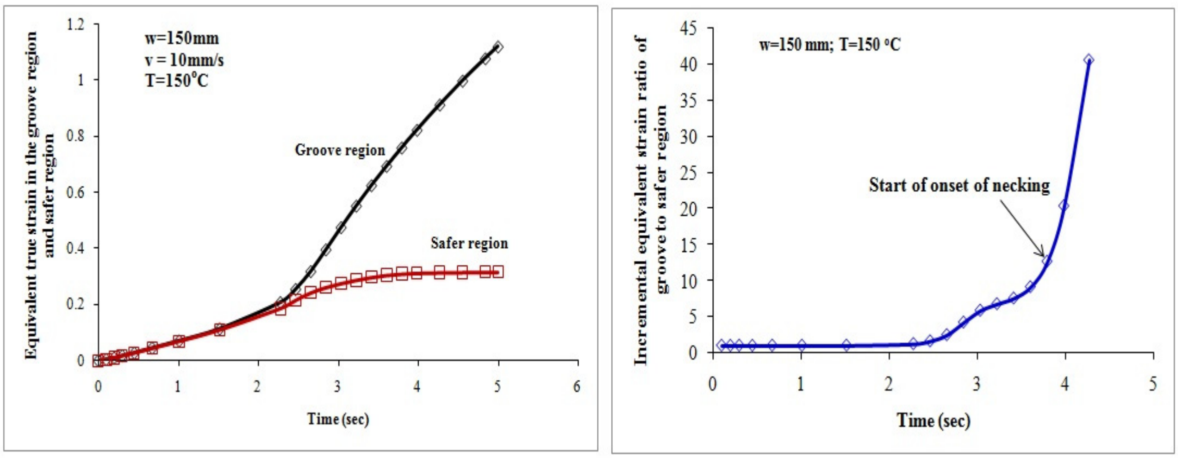

Fig. 7. Simulation result of strain in groove and safer region versus time and incremental strainratio of groove to safer region for AA5086 alloy

For M-K analysis, during deformation strain builds up in both groove and safer region, but the rate of strain accumulation in groove region is more as compared to safer region as groove region is thinner compared to safer region. After a certain moment of deformation, strain in safer region saturates while in groove region it keep on increasing which leads to onset of necking as shown in Fig. 7 (left). Fig. 7 (right) shows the incremental equivalent true strain ratio of groove to safer region versus time, as it could be observed that the moment onset of necking is initiated rate of increment in strain for safer region decreases which leads to saturation. The moment saturation is observed at that deformation stage, major and minor true strains of the safer region are evaluated (Fig. 8).

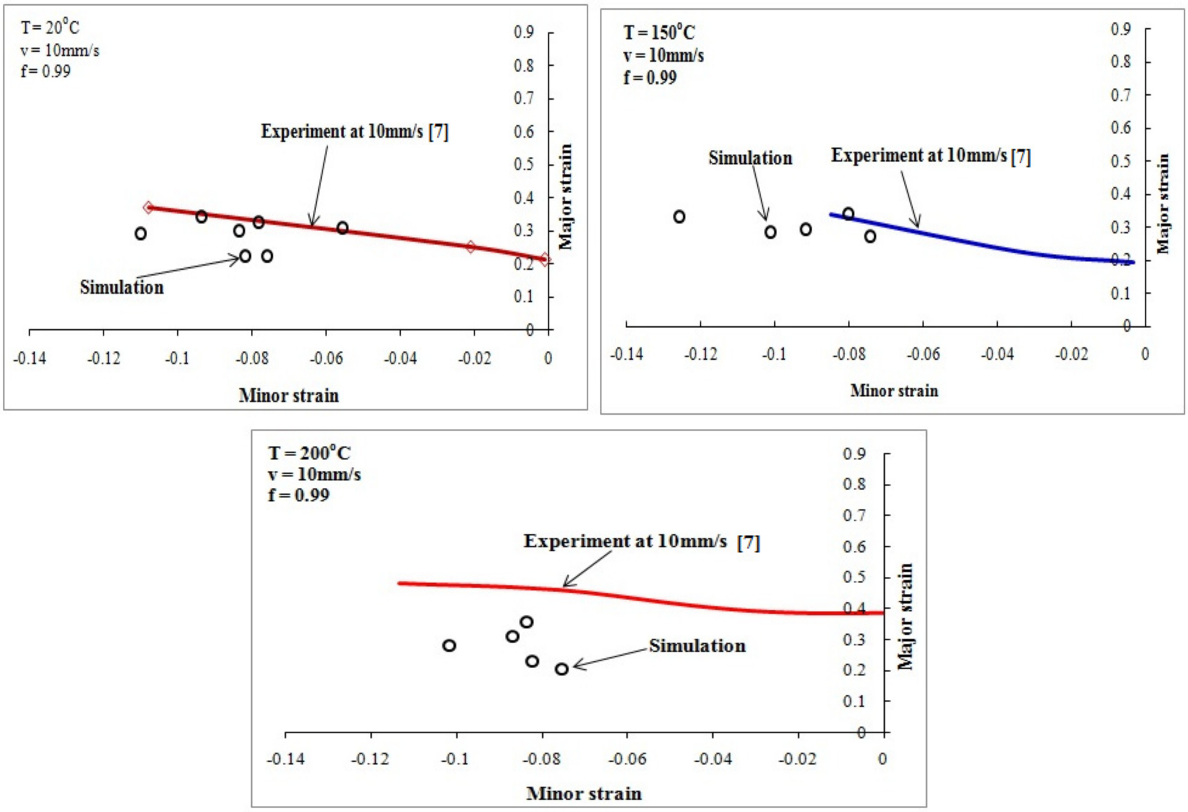

Fig. 8. Comparison between experiment and simulation result of FLC for AA5086 alloy

To capture strain data, contour of equivalent strain is plotted and mesh with maximum strain in the groove region is selected. For safer region, the selection of mesh needs to be done from the third or fourth set of elements just starting outside of groove region. Due to large value of *f* of 0.99 and tetrahedral mesh, first two sets of the elements in the safer region, i.e., outside the groove region has also large strain value, therefore in order to get saturation nature of the strain for safer region, mesh from the third or fourth set of elements is recommended to be selected. Fig. 8 shows the comparison between experiment FLC obtained by Chu et al. [7] and simulation results for three different temperatures of 20°C, 150°C and 200°C [7]. For *f* value of 0.99, FE model is able to predict the points closer to the experimental plot for lower temperature of 20°C and 150°C, but for higher temperature of 200°C predicted plots are deviating from the experimental one. It is thus shown the dependence of the *f* on temperature. Therefore, by choosing small value of *f* around 0.9 to 0.95, points obtained from simulation might predict experimental limit strain accurately and also closer to plane-strain (major strain axis) strain-path of FLD.

4. Conclusion

From the present work, it has been observed that at elevated temperature formability of magnesium alloy, WE43 is increased, with a decrease in the maximum flow stress. At higher temperature, there is a dynamic balance between hardening and softening which leads to longer elongation. In order to predict the experimental results accurately, selection of mesh at the shoulder region and modelling anisotropy at warm forming temperatures play a significant role. The M-K concept of employing a groove during FE simulation of tensile test would be beneficial.

The forming limit prediction during warm forming of AA5086 Al alloy is possible by M-K method. The predictions are encouraging, though plane-strain and stretching strain-paths are not simulated by changing the sample widths. The strain mapping approach, plot of equivalent strain Vs. time, is efficient to identify the onset of necking even at warm forming conditions. As the specimen is pulled, strain in groove region start growing rapidly, while it is slow in the safer region. This leads to saturation and thus enables identifying the onset of necking to construct FLD. Even in this case, selection of mesh for the safer region and the yield criterion chosen during modelling have a significant role in determining the saturation of strain and hence the accuracy of limit strain predictions.

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